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GLACIAL FEATURES IN THE SURFACE OF THE ALPS[1]

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The study of river action has been very much advanced in the Alps, whose torrents give magnificent examples of the destructive and constructive action of running water. But the surface features of this great European mountain chain do not all correspond to those which we might expect after a careful study of river action. Rivers seek to establish a normal curve, which grows continually gentler down-stream. The valleys of the Alps, however, do not show such a regular grade. The floors of the headwaters show many irregularities, and gentle grades alternate with steep ones. Instead of a slope curve, there is a succession of descending steps. Farther down we find for several miles a valley floor sloping normally; this floor has been aggraded by the river and often ends in a lake basin, where the normal slope is changed into a reversed one. Most of these features are not produced, but rather are destroyed, by river action. Indeed, we see how the rivers intrench themselves in the steep parts of the stair slope, and how they fill up the lakes, which generally occupy the lower part of their valleys in the Alps. In short, their action is directed toward removing the irregularities of their courses.

There is still one other important point in which the slope of Alpine valleys does not obey those rules which control normal valleys; the law of Playfair is not applicable to them. The mouths of the lateral

[1] This paper contains some results to which the author has arrived by researches on the Great Ice Age in the Alps, carried on together with Professor Brückner, of Halle. A detailed account of this study is given in a book entitled *Die Alpen im Eiszeitalter* (Leipzig: Tauchnitz). A part of the paper was read at the International Geographical Congress at Washington, September, 1904.

valleys are usually not accordant; they do not lie at the level of the main valley, but at a higher level; their rivers often tumble down in waterfalls to join the master-river, or they have cut into the floor of the lateral valleys a deep gorge, through which they whirl, and rush to reach the bottom of the main valley. These are the very well-known *Klammen* of the eastern, and the "gorges" of the western, Alps; and many waterfalls of this mountain chain lie at the mouths of the side valleys.

The cross-sections of our Alpine valleys are also other than what one might expect. The master-valleys have in general an extended flat bottom, at the sides of which rise very steep walls. At a certain height, steep slopes below change into more gentle ones above. Well-marked ledges separates the two slopes, and form distinct shoulders on both sides of the valleys—a condition not usually found elsewhere. That part of the valley which lies below the shoulders has often a trough-like appearance. The trough extends upward to that region in which the aggraded valley bottom is succeeded by a series of descending rocky steps, and here is often formed a very striking trough's end, by the cliff side of a high step. Above the shoulders the valley slopes are far from being regular; often they form cirque-like niches, at the bottoms of which little tarns occur. These are the *Kar* of the Alps, the "corries" of Scotland.

There are certain rules which control the occurrence of all these features. The heights at which the side valleys terminate above the main valley show a pretty regular arrangement. They describe a curve which slopes down regularly between the height above the trough end and that point where we meet with the last part of the reversed slope of the valley floor. The shoulders show a similar, but less regular, arrangement; they are also limited by the trough's end and the end of the last reversed slope of the valley floor; their height also decreases, though not regularly, between these two points. The whole arrangement leads to the conclusion that the trough has been excavated in an older valley with a higher floor; the shoulders are the intersections between the trough sides and the side slopes of the old valley. The hanging side valleys are parts of the old valley system which suffered little from erosion, and conserved their original depth. This condition is now generally accepted, since the connection

of all these phenomena has been recognized, but this conclusion is not in harmony with ideas which prevailed for a considerable period, when only *one part* of the irregularities of Alpine valleys was taken into consideration.

For some time the great Alpine lakes have been regarded as the only irregularities of the Alpine valleys, and the questions of Alpine geomorphology have included only the formation of the great Alpine lakes. Of the different ways in which valley lakes are formed, only two have been considered; namely, the hypothesis of warping and the hypothesis of glacial erosion presented by A. C. Ramsay. In order to understand the former, let us assume that the lower part of a normal river slope was elevated, or the upper part was depressed. The normal slope curve then would be changed into a curve with an ascending part having a reversed slope, and the part limited downstream by this reversed slope would be filled with water so as to become submerged. This idea, first suggested by Sir Charles Lyell, and later developed further by Rütimeyer and Heim in Switzerland, helps us to understand the transformation of some valleys into lake basins; but it leads to consequences which are not supported by observations in the field. Earth-movements which could reverse the slope curve of a master-river must also affect its branches; and if a part of its curve is depressed to form a basin, the affluents of this part must also be depressed, and their lower courses must be submerged in a manner similar to the basin formed by the depression of the floor of the master-valley. Lakes formed by the subsidence of part of a river valley must digitate into the side valleys. Contrary to this, the side valleys of the great Alpine lakes are not drowned at all, but they are hanging above the lakes, and their floors show no traces of depression. The digitations we find now and then in Alpine lakes have nothing to do with the drowning of true lateral valleys; they do not stretch toward the mountains from which the side valleys come, but extend in the opposite direction. They are related to the frequent valley bifurcations, which will be considered later.

The basins of the great Alpine lakes occupy only a part of the troughs of the Alpine valleys, and every hypothesis as to their formation must deal with the trough. The trough bears every evidence of

having been eroded in a former river basin, the side branches of which suffered less lowering than the main branches. This fact is now generally admitted by all who have studied the relation between the high-hanging valleys and the main valley, and it is generally acknowledged that the latter, in comparison with the former, has been overdeepened by erosive action. But there is still a diversity of opinion as to this action. Some authors, like Kilian, Garwood, and Frech, believe that it has been exercised by rivers, while the hanging valleys were occupied by glaciers and protected by them against the erosive action of water.

This idea ascribes to river-action phenomena such as are usually not developed by it. The trough does not bear the features of a common river valley; it has the width to which river valleys attain in their maturity, but it has not the normal grade which rivers always have in this phase of their development. Their slopes have the steepness of youth, as is proved by innumerable landslides occurring along them. It is a peculiar association of young and mature valley features we meet with in our large Alpine, trough-like valleys—an association which cannot be understood by the assumption of normal river action; and no attempt has been made until recently to show how it was brought about by rivers. As to the hanging valleys, however, there are not a few cases in which they were not occupied by glaciers. Therefore glacial action protecting their bottoms cannot have caused the elevation of their bottoms above those of the main valleys. The hanging valley is not a feature characteristic of glaciated regions only, the hanging mouth being confined to the latter.

He who wishes to examine the Alpine valleys in the light of river-work must not first take the valley floors into consideration; he must observe the river channels. There the law of Playfair has no application. While in the state of their maturity the surfaces of two rivers unite at the same level, their bottoms will not do so; the bottom of a larger, deeper stream generally lies deeper than that of its smaller and shallower affluent. The bottoms of side-river channels are hanging above those of the main rivers. We have here steps at the mouths, as in the Alpine valleys. While the surfaces of rivers grade down continually, their bottoms show irregularities which resemble those of the floors of some Alpine valleys. The forms of mature valleys

are determined by the laws which control the *surfaces* of moving liquids, while the forms of the Alpine valleys are governed by the rules controlling the formation of the *floors* of moving liquids. Thus, instead of the law of Playfair, the law of adjusted cross-sections comes into action.

There can be no doubt what particular moving liquid or quasi-liquid is related to the features of the Alpine valleys, since it has been recognized that all the greater Alpine lakes lie in the region of the old glaciation, and later researches have proved this for all the special features of Alpine valleys. The overdeepening, with all its accompanying features—the trough, the trough's end, and the lake lying in it, with its shoulders and the hanging mouths of side valleys—is confined to the area glaciated during the Great Ice Age, and the moment you leave this area you reach the normal features of mature valleys with accordant mouths of side streams; you reach mountains whose summits are not dissected by corries. The concurrence of Alpine valley troughs and old glaciers suggests the theory of origin by glacial erosion. The theory of glacial erosion was advanced by A. C. Ramsay for the formation of the Alpine lakes. We go a great deal farther than he when we apply that theory to the formation of the far more extended feature of the troughs in the Alpine valleys, for the lake basins occupy only those parts of the troughs which extend below the lowest parts of their circumferences.

The erosive action of the glaciers has very often been denied, and is even now denied by some, while it has been at various times vigorously supported. This diversity of opinion is caused by the fact that we cannot observe how actual glaciers act upon their bottoms, their work being concealed by their icy mass. We usually see only how the glaciers transport moraines and deposit them about their lower ends. The fact that stone avalanches not rarely fall down from the side walls of a valley on the surface of a glacier suggested the idea that the material of the surface moraines is due entirely to the action of weathering exercised on those cliffs which overlook the glacier. The study of the moraines on actual glaciers, however, has revealed more clearly the fact that they cannot be entirely derived from those cliffs, but that they come in large part from the bottom of the glacier. What effects are here produced by the glacier can be observed only

at those places which have been covered by the ice for some time, and then revealed again. Here we observe those very well-known *roches moutonnées*, polished and striated surfaces, which dip gently in the direction from which the glacier came, but which terminate abruptly in the opposite direction. In general, the rock surface is here limited by joints. It cannot be longer maintained that we have at those places the original surface of the rock before us. We stand rather before a quarry from which rock fragments were broken out and plucked away. This can be proved now and then by observation. At the Hornglacier in the Zillerthal Mountains, for example, I found near a *roche moutonnée* fragments which had been plucked out there and transported by the ice for some distance, slightly upward. They fitted perfectly into the quarry from which they were taken. Thus the *roches moutonnées* teach us that glaciers do not exercise a scouring action alone on their beds, as generally stated, but that they also effect a quarrying and plucking action, which is not always recognized. Therefore we will no longer call the two sides of a *roche moutonnée* "push side" and "lee side," but we prefer the expressions "scour side" and "pluck side," introduced by Shaler. Plucking forms the most important part of glacial erosion; it is exercised as well on the bottom as on the sides of its bed, and since the glacier can also transport fragments upward, it is enabled to adjust its bed to its mass and its movement.

The adjustment of its bed to its mass and movement is not confined to glaciers; the same occurs in rivers. The difference lies partly in the fact that the glaciers' beds, on account of the slowness of glacier movement, are far more conspicuous than the beds of rivers of equal capacity. The adjustment to which we refer is controlled by the necessity that through a given cross-section of a river or of a glacier must annually move the whole quantity of run-off or ice produced in the corresponding catchment basin. There is therefore a relation between the size of cross-sections (Q) and the mean velocities (V) of the liquids, on the one hand, and of area (A), precipitation (p), and evaporation or ablation (e), on the other, which may be expressed by the following equation:

$$VQ = A(p-e).$$

If there are no sudden changes either in the velocity of the moving bodies—those changes will always disappear in the course of time—or in the precipitation and evaporation or ablation of a certain region, then neighboring cross-sections will increase in the same way as the areas do. They will be nearly equal in size, if there is only a slight increase of the catchment basins between the two sections; they may be rather different if a sudden increase of the catchment basin occurs. If, for example, a river or glacier gets an important affluent, there will be a rapid increase in the size of its cross-section.

The arrangement of neighboring cross-sections is controlled by the fact that the surface of the moving liquid must have a slope. Their surfaces must continually decrease in height when we follow the direction of the movement, and where two moving fluids unite their surfaces must join at the same level. The surfaces of glaciers as well as the surfaces of rivers obey the law of Playfair, but their channels conform at the same time to the law of cross-sections. The large cross-section of a main river or a main glacier, as well as the smaller cross-sections of their affluents, have accordant surface junction, and therefore their bottoms must have different heights as long as the cross-sections are similar to each other, which is in general the case. The bottoms of side streams hang above the bottom of many rivers in the same way as the bottoms of side glaciers hang above the bottom of main glaciers. The hanging mouth is a feature of the bottom of moving liquids; the accordance, a feature of their surfaces. Since the river surfaces are the base levels of the country along their sides, they govern the heights of the bottoms of the valleys, which therefore, obey, the law of Playfair.

Every river bed shows inequalities which may be compared with the inequalities of the glacier bed. There is, however, one very marked difference. Most rivers constantly grow, and their cross-sections become therefore larger and larger. On the other hand most glaciers grow only to a certain limit; then they decrease by ablation until they terminate. Therefore their cross-sections will increase at first and then decrease. In a simple glacier the maximum cross-section will be found just at the snow-line; in a composite one, it may occur farther downward. Above and below this maximum cross-section the surfaces and bottoms of the cross-sections will

approach one another until they finally coalesce. While, however, the surfaces must be arranged in a descending order, the same is not the case with the bottom. It is stated from observation that glaciers can also move on reversed slopes as long as they have a sufficient surface slope; that is, as long as the surface slope is considerably greater than the reversed bottom slope. To keep up glacial movement, it is necessary that the curves of successive cross-sections be arranged in a descending order. If we therefore, have, at the lower end of a glacier, a series of cross-sections of diminishing size, their bottoms may rise, if their surfaces slope so steeply that their centers of gravity form a continually descending line. Therefore we find in the bottoms of glaciated valleys reversed slopes, and we must expect to find them chiefly near the ends of the old glaciers. Here, indeed, most of the larger lakes of the Alps are found.

The general arrangement of the Alpine glaciation during the Great Ice Age was the following: The interior valleys of the mountain chains were filled up with enormous, flat cakes of ice, of 2,000–2,500 ^{m} elevation, interrupted by the higher ridges, from which deep affluents poured into the *mer de glace.* Its surface sloped down in the center very gently, and with increasing steepness toward its rim. Under this steep marginal slope lie the existing and former lake basins of the Alps. The location of their reversed slopes indicates the region where the glacier's erosive action gradually ceased. It has long been recognized that the depth of these lakes is far greater in the south than in the north, but no adequate explanation has been given. This phenomenon is consistent with the fact that the marginal slope of the Alpine glaciation at the south side of the mountains was twice or thrice as steep as on the north side; here a far greater reversed slope could be overcome by the glaciers. It must be borne in mind, however, that thick morainic deposits occur at the lower ends of the troughs. The lake basins of the Alps, therefore, are not alone formed by glacial erosion; they are partially dammed up by the thick gravel deposits which the glaciers accumulated at their ends, and this accumulation assumes, in the south side of the Alps, a far greater thickness than on the north side, because it is concentrated over a less extended area. This damming up raises the levels of the Italian lakes far higher than those of the south German lakes, and the differ-

ence of the depths of those lakes is partly caused by this difference of accumulation.

The rule of the cross-sections helps us to understand not only the formation of the lake basins in Alpine valleys, but also how the trough's upper end was formed. We usually find it where there was a confluence of the glaciers in the upper parts of a valley, where the slope glaciers united to form the valley glacier. The mass of ice, coming from this semi-circular head, was pressed here into the diameter of the same circle. Now, in order to maintain a continuous movement, an increase of velocity was necessary at this place. This increased velocity must act on the bed of the glaciers until a sufficient depth is attained. Theoretically this depth must be 57 per cent. (that is, $\frac{\pi}{2} - 1$) greater than at the semi-circle from which the glaciers came.

The cross-sections of glacier-beds are in general, as was recognized long ago, U-shaped, which indicates that a certain relation between width and depth is the most appropriate one for the glacier's movement. This U-form is, however, only constant in homogeneous rocks. In places where there are sudden changes in the nature of rocks, we meet with changes in the shape of the trough. At those places we observe that the glaciers exercise a very strong selective erosion on their bottoms. Some rocks resist more than others, and here the glacier bed shows a remarkable adjustment to the nature of the rocks. Many steps in glaciated valleys are caused by highly resistant rocks. Now and then, but not at all regularly, an increase of width corresponds here to the decrease of depth of the glaciated valley. Conversely, a sudden increase of width in a glaciated valley is often connected with a diminution in the depth of the trough.

The study of the old glaciers of the Alps reveals that, as far as their movement is concerned, they consist of two parts. In their upper parts, where they were fed by numerous affluents, there was a *confluence* of ice in the main valleys corresponding to the confluence of waters which occurs there now. In their lower parts, however, they no longer received lateral affluents. Here they spread out fan-like on the plains at the foot of the mountain chain, or even in its interior, penetrating into those valleys which afforded them no affluents.

Regions of glacial *confluence* and glacial *diffluence* are sharply separated from each other. They have nothing to do with the feeding and melting part of the glacier, and are determined only by the presence or absence of lateral affluents. The confluence and diffluence of glaciers, therefore, may occur as well in its névé region as in its region of ablation, in its feeding, or in its dissipating part (according to H. F. Reid), but generally the confluence prevails in its upper parts and the diffluence in its lower parts. On the north side of the Alps the diffluence is excellently represented by the enormous ice fans in the German Alpen-Vorland, where formerly were the glaciers of the Rhine, the Isar, the Inn, and the Salzach, while in Switzerland the diffluence was hindered by the Jura Mountains so that no regular fans were formed. On the south side, the fan-like diffluence of the ice occurred partly in the Alps, and was really restricted to it in the region of the lakes north of Milan, which we will call Insubrian lakes after the ancient country of the Insubrii, whose capital was Milan.

Everywhere where a fan-like diffluence of the ice occurred its bed shows ramifications which have a spoke-like arrangement and slope toward their center. Thus, for example, in the fan of the old Rhine glacier. Lake Constance is the center of the fan, its western termination bifurcating into lakes Uberlingen and Zell. In two similar broad furrows, the rivers Schussen and Argen approach the lake from the north and northeast. Lake Constance is the palm of the hand, its western branches and the furrows of Argen and Schussen being fingers which stretch out to the rim of the old glacier. A similar arrangement is found in the fans of the old glaciers of the Inn and the Salzach, the trough of the valleys terminating by branching in the sub-Alpine plains; and every branch is followed by a river flowing toward the Alps, in the direction from which the ice came, thus marking the reversed slope of the bottom of the different branches of the ice which formed the ice-fan. The same features reoccur where the diffluence of the glacier took place in the mountains. Lake Como bifurcates, and the Como branch has no outlet. Its waters must first flow toward the Alps to reach the outlet at Lecco. On the east side of Lake Como a branch of the old Adda glacier penetrated into the Valsassina, whose waters flow toward the Alps in order to reach Lake Como, revealing a reversed slope. A fourth finger of the Adda

glacier passed over the Pass of Porlezza and reached the eastern deep part of Lake Lugano, which drains into Lake Maggiore. If the morainic deposits to the south of the eastern part of Lake Lugano were higher, that lake would discharge into Lake Como, and the relation of the eastern part of Lake Lugano to Lake Como would become very clear. It is also a finger-lake, lying around the palm-lake of Lake Como, but separated from it by a low pass.

The finger-lakes and finger-valleys, with their reversed drainage, are a very conspicuous feature in the regions of glacial diffluence. Many phenomena indicate that they were not originally there, and that their formation was connected with the diffluence of the glaciers. Lake Orta is a typical finger-lake in the region of diffluence of the old glacier of the Ticino, and has a reversed drainage. It occupies, however, a valley whose catchment basin has a peculiar arrangement, as if it would be drained toward the Po plain. It can be shown that the Lecco branch of Lake Como came very lately into use as an outlet for a branch of the Adda glacier. It can be further determined that the different fingers in the large fans of the glaciers on the north side of the Alps are younger than the gravels of the first glacial epoch. How glacial diffluence controls the formation of these features can be shown by the study of those forms which are originated by it.

When a glacier fills a valley above the height of the notches in its watershed, it flows over these notches, if it is not hindered by ice masses on the other side of the pass. By overflowing, it exercises on the pass a conspicuous erosive action, by which the pass is lowered and widened. This can be seen in all passes which have been overflowed by ice. On the St. Gotthard and on the Grimsel, ice-marks are very clear, *roches moutonnées* with their scour and pluck sides spread over the culminating surface, and little mountain tarns indicate that the glacier eroded flat basins. The longer the ice-action goes on, the more the pass is lowered; the height of the watershed is leveled down to the floor of the valley, into which the glacier pours, and a vast flat is formed which begins at the shoulders of the valleys from which the ice branched. Many Alpine passes belong to this type. They can be reached from the glacier valley only by a sharp ascent on its trough-side, while the descent into the neighboring

valley is very slow. This is the case with the Monte Ceneri, which opens in the left side of the valley of the Ticino, and allows one to enter the surroundings of Lugano from the north; with the Pass of Seefeld, through which you reach the valley of the Inn south of Munich; and with the famous Pass of Reschenscheideck, through which you pass from the lower Engadine to the headwaters of the Adige. The erosion of this pass was carried so far that the floor of the pass reaches the shoulder of the Engadine, and that some old affluents of the Inn were already diverted into the Adige. A further state of erosion of an old pass is shown by the situation of Lake Orta. Here the pass has been totally leveled down, and considerable accumulations of moraines south of it force its water northward toward the Alps. Finally, in Valsassina, the long-reversed slope is independent of the terminal moraines south of it. It is a branch of the trough of the Adda valley, which extends here into a side valley where it terminates obtusely. This series of different stages shows us how the watersheds can be moved to the outer rim of the old glaciation. This state, however, has not been reached elsewhere. Its establishment depends not only on the intensity of glacial action, but also upon the original features. A pass originally very high will stand far longer than a low one. This fact must be observed in those cases where the valley, reached by a branch of the ice, is overdeepened in a way similar to the main valley. Thus, for example, that branch which branched off the glacier of the Ticino valley at the Monte Ceneri overdeepened the valleys west of Lugano, which are now occupied by the west branch of Lake Lugano, and the branch of the Adda glacier, which branched off at Menaggio, and passed the saddle of Porlezza, has overdeepened the valley of Porlezza and transformed it into the lake basin of Porlezza, which is the deepest part of Lake Lugano. He who considers only the lake basins as the results of glacial erosion will be much puzzled by the interruption of the erosive action of a glacier by a pass. On the other hand, he who follows the whole development of glacial erosion will easily recognize its great effect also on the pass traversed by the ice, and he will perhaps be aware that the erosion on the pass itself was more considerable than that which formed a basin.

The diffluence of the ice is controlled by the rule of cross-sections,

as is the confluence. In the same way, as steps were formed at the places where glaciers met, other steps occur where branches occurred, for here there was a sudden diminution of the ice. There are steps of confluence in the region of confluence, and steps of diffluence in the region of diffluence. The steps of confluence are seen in the hanging mouths of side valleys; the steps of diffluence are hanging openings of those valleys which were entered by a branch of the ice. The height of both kinds of steps will generally be more considerable, the greater the difference between the main glacier and its affluent or diverting branch. Thus the step of diffluence of Valsassina east of Lake Como is higher than that of Porlezza west of this lake, and the branches of Como and Lecco divided at about the same level, since they were of nearly equal size. Here is a true bifurcation of branches, and a bifurcation of valleys follows the diffluence of the ice, if the openings of the neighboring valleys passed by the ice are so deeply eroded that they will be easily buried by the accumulation of river material which is being deposited in all overdeepened valleys since they were vacated by the ice. The bifurcation of the Rhine valley near Sargans, that of the Isère valley at Montmélian, and that of the Salzach valley near Zell am See are fine samples of valley bifurcation caused by glacial diffluence, and not, as often said, by capturing.

The establishment of a reversed drainage in consequence of glacial diffluence is very much helped by the accumulation of moraines. They surround the dissipating part of the glacier. They follow its sides as lateral moraines and surround its end as frontal moraines. In the glacier fans north of the Alps they form conspicuous landscapes. They are often watersheds between the reversed drainage of the fan and the drainage of its surroundings, which corresponds to the drainage of the ice-fan during its existence. Thus, for example, the terminal moraines of the Rhine glacier form part of the great European watershed between the northern seas and the Mediterranean. On the south side of the Alps the terminal moraines are still more conspicuous, and form amphitheaters around the ends of the overdeepened glacier beds. These are the so-called morainic amphitheaters of upper Italy, whose deposits partially dam up the Italian lakes. Those glaciers which ended in the Alps left their

terminal moraines in the valleys, where they separate the reversed drainage in the region of diffluence from a peripheral drainage. The latter has been partially formed by shoving away the original rivers which descended to the ground before it was entered by the glaciers. When the ice came, they could not continue their courses and must flow along its rim. Thus they were pushed from their old courses and driven into new ones, which surround the ends of the glaciers. Many of these shoved river courses are no longer in use, having often been captured by the headwaters of the reversed drainage, as, for example, the Mangfall in Bavaria, which for a long distance flows along the terminal moraines of the Inn glacier, until it makes an elbow at the place where it was captured by a stream flowing on a reversed slope. Other shoved river courses became stable, since they were driven into the valleys of other rivers. Thus north of the old glacier of the Dran the waters of the upper valley of the Gurk were shoved by the rim of the ice into that valley which is now that of the middle Gurk, and which formerly had its own river. Here the moraine of the glacier along which the Gurk was shoved is still visible. In other cases the moraines are insignificant, especially where the glacier ended in a deep valley, and the course of shoved rivers can be traced only by the erosive action exercised along the glacier, cutting gorges into the projecting parts of the valley side. A magnificent example of such a shoved river can be followed on the left slope of the valley of the Sesia in upper Italy below Varallo. By their erosion on mountain passes, by establishing reversed slopes in their terminal regions, and by shoving the rivers coming from non-glaciated regions, the old glaciers of the Alps have profoundly modified, especially near their ends, the preglacial hydrography of the Alps.

The traces of glacial action in the Alpine valleys extend beyond the limits of the trough. Near the ends of the ancient glaciers the troughs are overlooked by moraines, which now and then are located directly on the shoulders. In the interior of the mountains the striated and rounded surfaces reach far above the shoulders, and there is a very marked scoring limit which separates those parts of the valley slopes which have been buried under the ice and rounded by it, from the higher, ragged slopes, which suffered by weathering. The

chamfer at the scoring limit (*Schliffkehle*) exhibits clearly a sapping action of the ice exercised along its sides, and this lateral erosion seems to have been strongest near the surface of the glacier. This condition is perhaps caused by the more brittle state of the glacier ice near its surface, while the trough indicates that the glaciers eroded intensively downward at their bottoms.

Glaciers not only exercise a sapping action along their sides, but also at their very heads, if they are here overlooked by rock cliffs. There is always a marginal crevasse, called in German *Randspalte* or *Bergschrund*, which separates the moving ice from the rocks which overlook it. The material loosened here by weathering falls down from the rock walls into this crevasse and arrives at the bottom of the névé, where it is pushed forward by the moving mass grinding the bottom of the glacier. By this, not only the formation of screes around the glacier is hindered, but also the surrounding cliffs are constantly attacked, for the erosive action begins just at their foot and saps them. Glaciers, therefore, which are formed on slopes in broadly open valley basins, surround themselves finally by cliffs, which are pushed backward much as are the cliffs around the gathering basin of a torrent. The bottoms of hanging glaciers may be transformd much as are the floors of main valleys which are occupied by glaciers. The rule of the cross-sections is equally applicable to them. A glacier, for example, which ends on the slope can erode the central parts of its bed below the level of its lower end and thereby establish reversed slopes. Thus the original broadly opened valley basin will be gradually changed into a sharply limited niche with a basin on its bottom. The cirquelike form originating in this way is the *Kar* or "corrie." It differs essentially from that cirque which forms the end of a valley trough, though there is often much similarity in their mere appearance. The trough's end is formed in the bed of a glacier; the corrie at the head of the glacier. The ice moves down over the cliffs of a trough's end, while it moves away from the cliff of a corrie. After having climbed over the walls of the trough's end, one arrives at a flat, formerly occupied by a hanging glacier usually surrounded by cliffs. Then one arrives at a corrie or a series of corries. An ascent of the walls of a corrie always leads one to the crest of mountains. Therefore we distin-

guish between cirques in valleys and cirques on slopes, between trough's ends and corries.

The forms produced by small glaciers on the slopes of the valleys vary very much. One feature is produced everywhere where the glaciers are overlooked by rocks; that is, the corrie cliff, originated by sapping. The formation of a basin at the foot of these cliffs depends on the same conditions as the formation of a basin in a valley occupied by a glacier; it is only formed where the successive cross-sections, after having increased, again, diminish—a condition which is regularly found in those glaciers which end on the slope on which they began. The true corries, with basins in their bottoms, are therefore mostly the beds of isolated hanging glaciers which did not descend far below the snow limit, and their bottoms lie nearly at the level of this limit. But if on the slopes we have glaciers which feed the valley glaciers, then we have usually to deal only with an increase of their cross-sections, and their bottoms descend without interruption somewhat below the surface of the valley glaciers. Then an *open corrie* is formed, the bottom of which often terminates rather abruptly a little below the scoring limit along the sides of the glacier valley. There are many transitions between the true, closed corrie and the open corrie; for there are many transitions between isolated hanging glaciers and affluent hanging glaciers. Now and then we find closed corries along the sides of a valley glacier, formed by its lateral affluents, which were dammed up by it. On the other hand, we find open corries as the beds of local, isolated glaciers, which lay on slopes the steepness of which was not favorable to the establishment of reversed slopes.

Closed corries prevail in the eastern parts of the Alps, where this mountain chain did not reach far above the snow-line of the Great Ice Age. Now and then we find here mountains with a single corrie or *Kar*, whose steep cliffs contrast strongly with the rounded and smoothed forms prevailing around it. Other summits are rather crowded with corries, which have eaten back so far that there is only a part of the old rounded mountain surface conserved. In other cases the last trace of the latter has disappeared, and there is a sharp crest line which separates the corries or *Kare* of opposite sides. If this crest disappears under the attacks of the glaciers, then a flat surface

will be formed in the place of a former dome-shaped elevation. This surface will, however, not reach below the snow limit. Thus by the action of isolated hanging glaciers mountain summits may be degraded nearly to the level of main glaciers, so far as they lie above the snow-line.

Open corries prevail in the highest parts of the Alps, in Tyrol and in Switzerland. Their forms vary according to the height of the valley slopes above the level of the main valley glaciers. The higher these slopes are, the steeper they become, and the steeper then the slope of the bottom of the corrie. The steeper this slope, the smaller becomes the angle between it and the surrounding cliffs, and in those parts of the western Alps which reached highest above the surfaces of the neighboring valley glaciers the cliffs and the steep bottoms of the open corries nearly unite, to form very steep cliffs, the feet of which are and were constantly attacked by steep hanging glaciers formed by snow avalanches and interspersed with stones which have fallen down. The cliffs of two opposite glaciers of this kind usually intersect at a very acute angle, and form very sharp ridges whose summits are needle-like. These are the features in the Mont Blanc region, with its *aiguilles*. The height of all these sharp crests is determined by their elevation above the neighboring valley glaciers. Neighboring crests have, therefore, nearly uniform heights, and all rise in height in that direction from which the ice radiates or radiated. Therefore, seen from a distance, the centers of glaciation of the Great Ice Age, which are still today the scenes of a very strongly developed glaciation, appear as extended domes, which are very much dissected by glaciated valleys, and from which rise only a few isolated peaks, in places where the rocks resisted best the attacks of weathering. The Mätterhorn and the Gross-Glockner are types of these horns of highest resistance. They show clearly that the actual height of the sharp mountain crests of the Alps is far from being an original one. It is determined by destructive processes, the attacks of which still go on above the actual glaciers, constantly lowering the crests and the summits. The latter fact leads to the conclusion that our process of destruction is a rather modern one, for if it had lasted for a longer time, it would long ago have removed the whole of those crests projecting above the glaciers. It was believed that the crests of the

mountains had been protected during the Great Ice Age by a covering of snow, and that the destruction has since begun. But the fact that the surfaces of the old glaciers served as a base-level of destruction, as the surfaces of actual glaciers do, leaves no doubt that also in the glacial period the destructive process went on. Its youth must, therefore, result from other causes, as has been believed until now. There are many reasons for assuming that the Alps were elevated during the Great Ice Age, and that this elevation was a true vertical upheaval. The youth of the high mountain crests might be caused by such a recent upheaval, still going on.

That the surfaces of the valley glaciers serve as a base-level of destruction for the hanging glaciers is a fact which corresponds to the same relation between the surfaces of side and main rivers. The other fact, that also the snow-line is such a level, helps us to understand the relation between the rates of glacial and fluviatile erosion. The snow-line becomes visible in the forms of those mountains which rise above the snow-line of the glacial period in such a way as to show that above it the destruction of the mountains went on more quickly than farther down. The sudden increase of the destruction of mountains cannot be directly caused by a sudden climatic change between the elevations below and those above that line, causing a difference of weathering. We know there is such a gradual transition of the climate in the neighborhood of the snowline, that it is very difficult to recognize the climatic features determining its position. The increase of destruction above the glacial snow-line is not due to an increase of weathering above it but is caused by the development, of a new agency, degrading land at a faster rate than the running water. This agency is the glacier ice.

Ice does not protect its bottom, as commonly believed; it attacks vigorously. These attacks become most visible where glaciated surfaces extend into the neighborhood of non-glaciated areas. There we have a continual sapping of the latter. They cannot be as easily recognized on surfaces which were totally covered with ice, for these suffer by a general degradation. Therefore mountains which have been totally covered with ice will not exhibit the same features as those which had only local glaciers. They will have no corries, and they will conserve, under their covering of ice their rounded surface;

but this will be degraded and everywhere lowered. Thus we see, besides those mountains into which closed and opened *Kare* have been gnawed, others which projected equally above the glacial snow-line, which still conserve more or less completely their preglacially rounded forms. They were totally buried under the ice.

The actual surface features of the Alps do not at all correspond to those of a water-worn mountain range. Their conformation is mostly due to ice-action, which becomes most visible where the old glaciation ceased. It shows an adjustment to ice-action which is not quite perfect everywhere, since it probably has been disturbed by earth-movement in its highest parts, and by the action of the receding ice during its oscillations in postglacial time. These oscillations have led to the deposition of morainic material at places where erosion had before been active, and to the increase of erosion at other places. They have only slightly modified the general features worked out during maximum glaciation. We must conclude, therefore, that the durations of the maxima of glaciations, surpassed considerably the times of the increase and recession of glaciation, that is, the pre-glacial and postglacial times.